Are you violating your op amp’s input common-mode range?

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4/25/2011 7:22 AM EDT

Understand this critical op amp parameter and how it can be the source of mysterious misbehavior and inconsistent performance.

(*Editor's note*: several small errors crept into this article. They have been corrected in the text. For those who are re-reading this article, the changes are also called out explicitly at the very end, below the acknowledgment. We apologize for any confusion.)

You went through a process to select an operational amplifier (op amp) for your circuit based on the parameters most critical to your application. Some of the parameters you reviewed may have included supply voltage, gain bandwidth product, slew rate, and input noise voltage, to name a few.

You also accounted for input common-mode range, a key parameter important for all op amp applications in your circuit, right? If your answer is *no*, then you are highly encouraged to continue reading this article. Even if your answer is *yes*, you may still find this material useful.

Engineers who have worked with op amps throughout their careers likely have experienced situations where an op amp was behaving in an unexpected manner. The nice thing about op amps is that the output often tells the story. In many cases, if something is not “quite right”, it shows up in an obvious way at the output pin. Undesirable output waveforms can be caused by limitations at the output stage. Perhaps an oscillation is observed that is caused by too much capacitance on the output. Or maybe clipping occurs before reaching the full rail voltage because the output stage is limited to voltage swings less than the supply rail voltage.

It is also possible for strange behavior to appear at the op amp’s output that has nothing to do with the output stage. Sometimes the undesirable output signal may result from something wrong at the input side of the device. One of the most common issues experienced with op amps is violation of the device’s input common-mode range. But what exactly is *input common-mode range*, and what is the impact of violating or exceeding it?

Defining input common-mode range

When speaking of op amp inputs, input common-mode voltage (V_{ICM}) is one of the first terms of which an engineer thinks, but may lead to some initial confusion. V_{ICM} describes a particular voltage level and is defined as the average voltage at the inverting and non-inverting input pins (**Figure 1**).

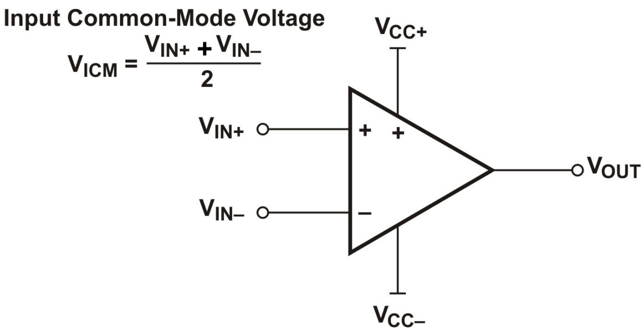

Figure 1: Input common-mode voltage for an op amp.

It is commonly expressed as:

$V_{ICM} = [V_{IN}(+) + V_{IN}(–)]/2.$

Another way to think of V_{ICM} is that it is the voltage level common to both non-inverting and inverting inputs, V_{IN} (+) and V_{IN} (–). As it turns out, in most applications V_{IN} (+) is very close to V_{IN} (–) because closed-loop negative feedback causes one input pin to closely track the other such that the difference between V_{IN} (+) and V_{IN} (–) is close to zero. T

This is true for many common circuits, including voltage followers, inverting, and non-inverting configurations. In these cases it is commonly assumed that V_{IN} (+) = V_{IN} (–) = V_{ICM}, since these voltages are approximately the same.

Another term used to describe op amp inputs is *input common-mode range* (V_{ICMR}), or more correctly *input common-mode voltage range*. This is the parameter most often used in datasheets and is also the one where circuit designers should be most concerned. V_{ICMR} defines a *range* of common-mode input voltages that results in proper operation of the op amp device, and describes how close the inputs can get to either supply rail.

Another way to think of V_{ICMR} is that it describes a range defined by V_{ICMR_MIN} and V_{ICMR_MAX}. As shown in **Figure 2**, V_{ICMR} is described by:

$V_{ICMR} = V_{ICMR\_MAX} – V_{ICMR\_MIN}$

Where:

V_{ICMR_MIN} = limit relative to VCC – supply rail

V_{ICMR_MAX} = limit relative to VCC+ supply rail

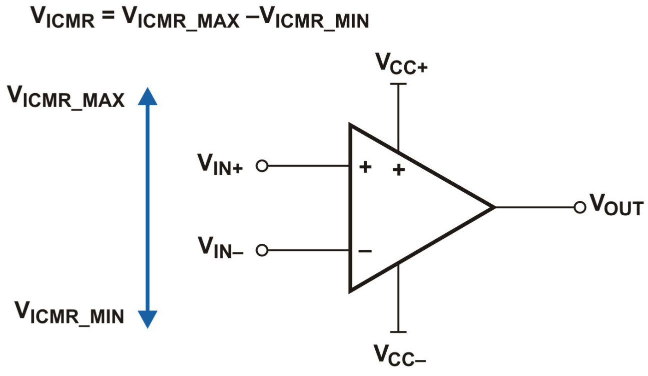

Figure 2: Input common-mode voltage range for op amp.

When V_{ICMR} is exceeded, the normal linear operation of the op amp is not guaranteed. Therefore, it is critical to ensure that the entire range of the input signal is fully understood and that V_{ICMR} is not exceeded.

Another point of confusion may be that V_{ICM} and V_{ICMR} are not standardized abbreviations, and various datasheets from various IC suppliers often use different terminology including V_{CM}, V_{IC}, V_{CMR}, etc. Consequently, it is necessary to understand that the specification you're looking for is more than a particular input voltage – it is an *input voltage range.*

V_{ICMR} varies among op amps

The input stage of an op amp is dictated by design specifications and the type of op amp process technology used. For example, the input stage of a CMOS op amp is different than that of a bipolar op amp, which is different than that of a JFET op amp, etc. While the specific details of op amp input stages and process technologies are beyond the scope of this article, it is important to note these differences exist among various op amp devices.

Table 1 shows several examples of op amps from Texas Instruments (TI) and their V_{ICMR}. The Max Supply Range column describes split-supply and single-supply (in parentheses) limitations. From the table it is clear that the input range, V_{ICMR}, is quite different from op amp to op amp. Depending on the type of device, V_{ICMR} may fall within or beyond the supply rails. Hence, never assume that an op amp can receive a particular input signal range until it is verified in the datasheet specifications.

Device	Technology	Max Supply Range (V)	V_{ICMR_MIN}	V_{ICMR_MAX}
TLE2062A	JFET input	Vcc+/– = +/–19V (38V)	(Vcc-) + 3.4V	(Vcc+) – 1V
TLC2272	LinCMOS	Vcc+/– = +/–8V (16V)	(Vcc-) – 0.3V	(Vcc+) - 0.8V
TL971	BiCMOS	Vcc+/– = +/–7.5V (15V)	(Vcc-) + 1.15V	(Vcc+) – 1.15V
OPA333	CMOS/R-R input	Vcc+/– = +/–2.75V (5.5V)	(Vcc-) – 0.1V	(Vcc+) + 0.1V
OPA735	CMOS	Vcc+/– = +/–6V (12V)	(Vcc-) – 0.1V	(Vcc+) – 1.5V

Table 1: V_{ICMR} examples for several different types of op amps.

One special case worth mentioning for wide input ranges is the *rail-to-rail input* op amp. Although the name implies an op amp whose input can span the entire supply rail range, not all rail-to-rail input devices cover the entire supply range as many might assume. It's true that many rail-to-rail input op amps do span the entire supply range (such as the OPA333 in Table 1), but there are others

that fall a little short and are misleading in their description. Again, it is critical to review the specified input range in the datasheet.

Examples of violating V_{ICMR}

Violating V_{ICMR} is commonly seen in single-supply op amp applications where the negative rail is often ground, or 0V, and the positive rail is some positive voltage such as 3.3V, 5V, or higher voltages. In these applications the input signal range typically is not very wide, and the input signal and V_{ICMR} must be well understood to make sure proper op amp operation results. If V_{ICMR} is violated, undesirable output behavior can result such as clipping the signal at voltage levels lower than expected, voltage shifts in the output signal, phase reversal, or the output reaches one of the supply rail voltages prematurely.

To better understand the effects of exceeding V_{ICMR}, we created some examples with violations. We selected two op amps with different V_{ICMR} specifications to demonstrate these effects. We chose these devices because they have rail-to-rail outputs to rule out limitations due to the output stage. The single-supply voltage follower circuit in **Figure 3** was used to capture waveforms for both devices. All data was captured on a lab bench at ~25°C room temperature.

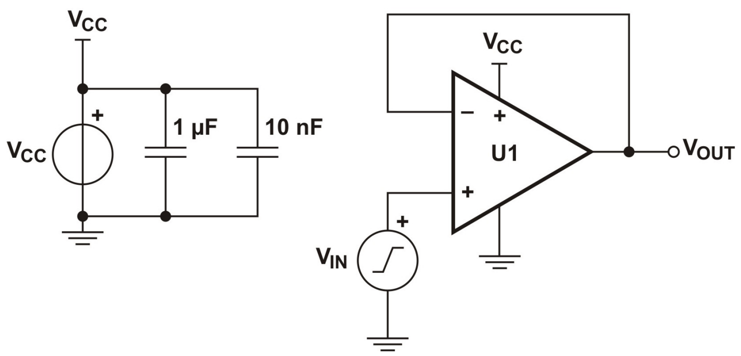

Figure 3: Single-supply voltage follower circuit used for evaluating V_{ICMR}.

Example 1

For the first example, we chose a TLC2272 op amp and supplied it with V_{CC} = 10V. The datasheet describes its typical V_{ICMR} range as –0.3 to 4.2V for a 5V supply voltage at 25°C. Note the input limitation near the positive supply rail, at .8V below V_{CC} (or V_{CC} –.8V). In this example V_{CC} = 10V is used and the resulting input limit near V_{CC} is estimated to be about 9.2V.

To test the circuit, we apply a 300 Hz sine wave with DC offset of $V_{CC}/2$ = 5V to the input. The AC amplitude is adjusted until a change is observed at V_{OUT}. As shown in **Figure 4**, when 10 Vp-p input is applied the V_{OUT} shows a clipped signal near the positive rail, but not near the negative rail. This undesirable behavior near the positive rail is what we should expect, if the input exceeds V_{CC} – 0.8V, or in this case 9.2V. For V_{IN} levels below 9.2V and down to 0V, V_{OUT} shows a proper waveform, as expected.

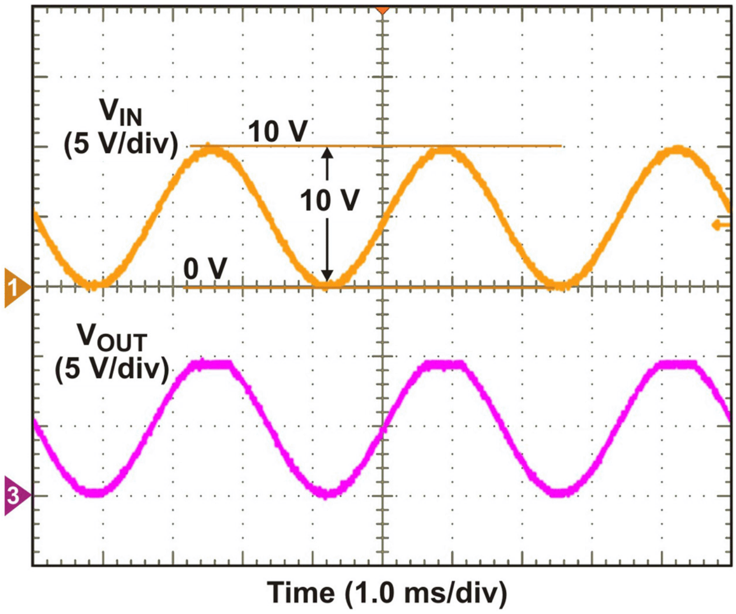

Figure 4: V_{OUT} of TLC2272 shows clipping when V_{IN} (Ch1) exceeds 9.2V.

Example 2

In the second example, a TL971 rail-to-rail output op amp is used in the Figure 3 voltage follower circuit, but with different results. Here, the op amp is supplied with a 5V single supply, such that V_{CC} = 5V. From the datasheet specifications, the guaranteed V_{ICMR} range spans 1.15V to 3.85V, or roughly 2.7 Vp-p centered at $V_{CC}/2$. A 1-kHz sine wave is applied with a DC offset of 2.5V. The V_{IN} amplitude is adjusted from 200 mVp-p to larger levels until a change is observed at V_{OUT}.

With V_{IN} centered at $V_{CC}/2$ = 2.5V, V_{IN} is increased to 2.7 Vp-p with expected linear behavior at V_{OUT}. As V_{IN} is increased up to about 3.5 Vp-p (centered at 2.5V), V_{OUT} continues to follow V_{IN} and exhibits proper op amp behavior. Note that the linear behavior is better than what we might expect from the datasheet limits for V_{ICMR}, but it still exceeds the guaranteed limits.

As V_{IN} is increased slightly more to 3.52 Vp-p, V_{OUT} starts to exhibit non-linear behavior near both the positive (5V) and negative (0V) rails (**Figure 5**). V_{IN} is further increased to 4.2 Vp-p to clearly exceed V_{ICMR}. As the input peak exceeds the limit near the positive rail, the signal at V_{OUT} rails out as it jumps up to the positive rail (5V) and stays there until V_{IN} returns to an acceptable range (**Figure 6)**. As the input drops below the limit near the negative rail, the signal at V_{OUT} exhibits a phase-reversal as it jumps to mid-rail (2.5V) and tracks V_{IN} with an offset until V_{IN} increases to an acceptable voltage within the V_{ICMR}.

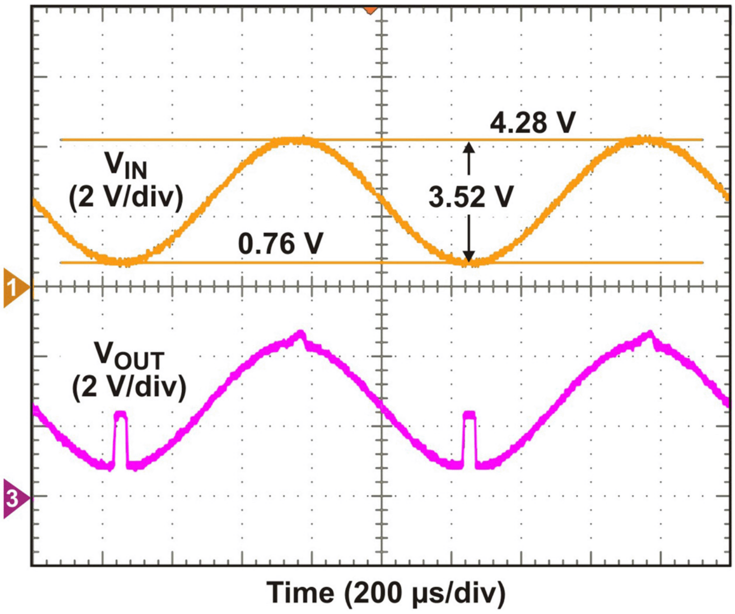

Figure 5: Onset of non-linear output behavior for TL971 when V_{IN} = 3.52 Vp-p.

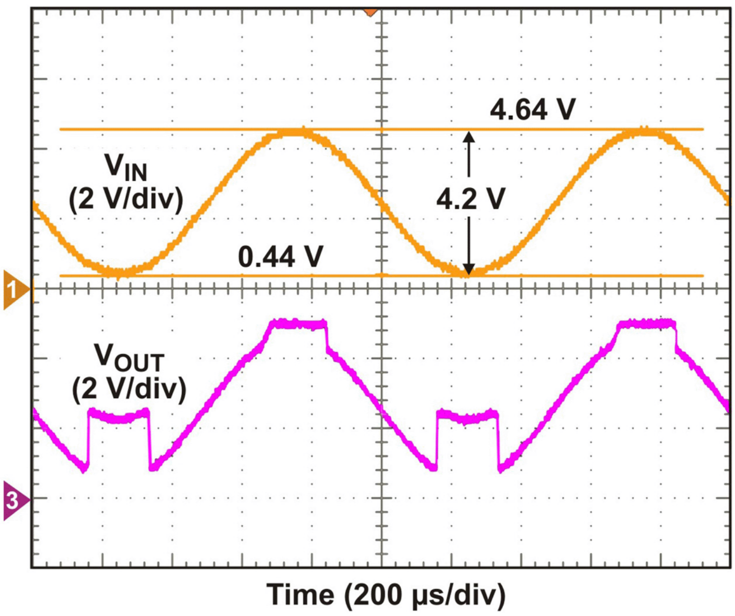

Figure 6: Non-linear output behavior for TL971 when V_{IN} = 4.2 Vp-p.

These examples show that different non-linear behavior can result from different types of op amps when V_{ICMR} is exceeded. Even though phase reversal resulted in the second case, note that phase-reversals do not occur in *every* op amp when V_{ICMR} is violated – it just depends on the op amp.

DC analysis

In the previous examples, we used an AC signal to evaluate V_{ICMR} for an op amp circuit. Another useful test is to apply a DC voltage source to the input of the circuit in Figure 3. While varying the

DC input, the output level behaves in a similar manner, except that it won't be varying over time. Depending on the type of circuit, AC or DC analysis (or both) may be useful in the early evaluation of the op amp.

Overcoming a V_{ICMR} problem

What if you discover that you can't meet the V_{ICMR} requirements of your op amp late in the design process? Maybe the other device parameters are ideal for your application, and it is really difficult to change the device. One or more of the following options might be a potential solution:

(a) If the input amplitude is too large, use a resistor divider to keep the signal within proper range of V_{ICMR}.

(b) If the input signal offset is the problem, try using an input biasing or DC offset circuit to place the input signal within the specified V_{ICMR} range for the op amp.

(c) Change the device to a rail-to-rail input op amp that meets all your other requirements.

References

- Download datasheets for op amps used in these examples here: **OPA333**, **TL971**, **TLC2272**.
- Download your free version of TINA-TI™, a SPICE-based analog simulation program used in these examples: **www.ti.com/tinati-ca**.

Conclusion

When selecting an op amp, remember that input common-mode voltage range is one of the most critical specifications to understand. If the device's input cannot accept the levels or range of your input signal, most certainly you will experience problems at the output. Check this important detail first and you'll thank yourself later when your circuit is operating properly – as expected!

About the Author

Todd Toporski is a Member of Group Technical Staff at Texas Instruments where he specializes in Analog Applications. Todd received his BSEE degree from Michigan Technological University in Houghton, Michigan, and his MSEE degree from The Georgia Institute of Technology, Atlanta, Georgia. He holds a number of patents in the areas of radio, audio, and power electronics. Todd can be reached at ti_toddtoporski@list.ti.com

Acknowledgements

The author wishes to thank Lucian Popa, a co-op student working at TI at the time this article was written, for his assistance in capturing the waveforms used in this article, and Art Kaye for his useful review and feedback.

Corrections made

- Figure 4 caption: Replaced **TL971** with **TLC2272**
- Figure 5 caption: Replaced **TLC7722** with **TL971**
- Figure 6 caption: replaced **TLC2272** with **TL971**
- Equation in Figure 1: Changed with “–” sign instead of “+” sign
- Equation $V_{ICM} = [V_{IN}(+) - V_{IN}(-)]/2$ changed to $V_{ICM} = [V_{IN}(+) \mathbf{+} V_{IN}(-)]/2$